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MIXED LIQUOR SOLIDS SEPARATION BY FLOTATION[a]

By Michael C. Mulbarger,[1] and Donald D. Huffman,[2] A. M. ASCE

INTRODUCTION

The first full-scale application of dissolved air flotation for mixed liquor solids separation has been incorporated at a new 1.0 mgd Water Pollution Control Facility in Prince William County, Virginia (8). The results of a field investigation at this facility are reported herein. The data indicate that conventional design criteria do not fully characterize flotation performance, and a new parameter, developed from a theoretical relationship derived by Howe (4), is offered as a rational design and operational guideline. Flotation performance is analyzed in terms of float detention time and process design. Cost-quality comparisons of mixed liquor solids separation by flotation and gravity sedimentation are presented.

PLANT DESCRIPTION

The performance of any solids-liquid separation unit is affected not only by its own physical design but also by the unit processes which precede it. At this facility, the dissolved air flotation unit is preceded only by pretreatment facilities and a biological reactor with mechanical aeration. Fig. 1 shows the

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flow diagram for the primary aeration and flotation system and Table 1 furnishes applicable design information.

INVESTIGATIVE PLAN AND TECHNIQUES

The primary investigative plan was to subject the flotation unit to a variety of solids and hydraulic loads, and to observe and record its performance in relation to specific design and operational criteria. Hydraulic variability was

TABLE 1.—PHYSICAL CHARACTERISTICS OF PRIMARY AERATION AND FLOTATION SYSTEM

Item (1)	Aeration unit [a] (2)	Flotation unit [b] (3)
Length, in feet	56.7	69.2
Width, in feet	28.3	40.0
Depth, in feet	14.0	10.7
Volume, in gallons	168,000	220,000
Detention time based on $Q + R$, in hours	3.8	3.4
Surface overflow rate in gallons per day per square foot of tank surface	Not applicable, mixers consist of two 30 horsepower turbines with 5 axial blades on top and 4 flat blades on bottom	570

[a] D-O Aerator equipment manufactured by Dorr-Oliver, Inc., Stamford Conn.
[b] Dissolved air flotation equipment manufactured by Rex Chainbelt Inc., Milwaukee, Wisconsin.
Note: Mention of specific proprietary equipment is for information purposes only and does not constitute endorsement by the Federal Water Pollution Control Administration and the U.S. Department of the Interior.

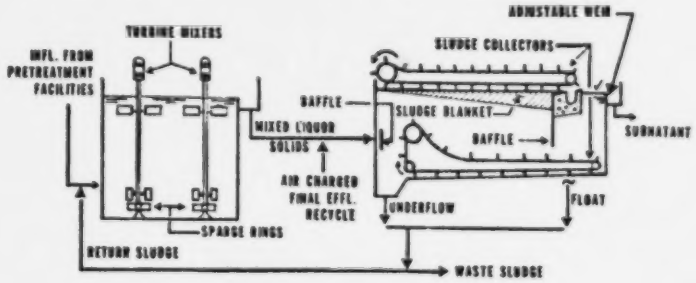

FIG. 1.—FLOW DIAGRAM: PRIMARY AERATION AND DISSOLVED AIR FLOTATION SYSTEM

achieved by the difference between dry weather and storm flows (0.6 mgd to 1.2 mgd). Mixed liquor suspended solids concentrations were studied in the range of 960 mg per l to 8,000 mg per l. Only those data points with the flotation system in potential balance, (i.e., float solids concentration; return sludge volume ≥ mixed liquor suspended solids concentration; influent flow volume), were used for evaluation.

Variables such as the float detention time, defined as the time required for the surface sludge collectors to traverse the length of the tank, and pressurization (40 psig and 50 psig) were adjusted daily during each four day experimental run. The correct skimming depth, varied by an adjustable weir, was established prior to the initiation of the experimental program.

Skimmer depth setting is a function of the sludge pumping capability (40 gpm to 50 gpm for this facility) and the need to return as concentrated a sludge as possible. As sludge concentration decreases as a function of the depth from the float surface (6), a shallow skimming depth of less than an inch was used and held constant throughout the investigation. The pressurized return was maintained at 400 gpm.

All sampling was conducted around-the-clock and flow proportional subnatant samples and constant volume sludge samples were collected every 2 hr. The basic 50 run experimental program was initiated in September, 1968, and completed in March, 1969. This long period was caused by the need to reestablish equilibrium biological conditions each time the activated sludge organic loading rate was changed. All analytical procedures were performed in accordance with Standard Methods (9).

RESULTS AND ANALYSIS

Design and Operational Variables.—The variables affecting flotation performance are pressure, recycle volume, feed solids concentration and volume, sludge detention period, air/solids ratio, solids and hydraulic loading rates, liquid temperature, and type and quality of sludge. An additional variable, not studied herein would be type and quantity of chemical aid.

Type and Quality of Sludge.—In the primary aeration system, the turbine mixers physically shear the activated sludge floc to consistently produce a low sludge volume index, SVI. For example, although the activated sludge system was loaded from 0.3 to 1.8 lb COD per lb MLVSS-Day in an attempt to study different microbial populations, the mean and standard deviation SVI for the study was only 58 ml per gm ± 8 ml per gm. Clearly, the added variable of changing biological conditions was dominated by the shearing action in the primary aerator. The sheared biological floc influences flotation performance by producing a readily concentrated sludge (denser float solids) and a difficult to separate colloidal solids suspension (poorer effluent quality).

Solids Load.—The solids loading rate, in pound-solids per square foot per day, is often presented as indicative of process performance and is a widely used design parameter (5). Generally, higher loading rates will impair process performance. Examination of this parameter shows that tank surface areas are sized as a function of the volume and concentration of solids in the feed stream. In a thickening application, where essentially all variables except feed solids concentration are held constant, use of the solids loading rate is probably justified, at least in terms of predicting thickened sludge characteristics.

Air/Solids Ratio.—The air/solids ratio, in pounds per pound is normally used as a design tool in combination with the solids loading rate. This ratio considers liquid temperature as it affects air solubilization, recycle volume, pressure, and feed solids concentration and volume. A recommended design standard is 0.02 lb per lb (2). Ettelt (3) states that effluent quality is not predictable for this parameter except for very low air input rates or high solids loading rates. When the air/solids ratio is applied with the solids loading rate, all controllable variables are considered except the additional hydraulic load associated with recycle. The general practice is to then check the surface overflow rate so as not to exceed a given limit, normally 1,150 gpd per sq ft. The Prince William County facility, with a design surface overflow rate of 570 gpd per sq ft, can be classified as a conservative design.

In separation of mixed liquor solids by flotation, dynamic and highly variable hydraulic conditions are encountered. There is also a need to predict effluent quality as well as float concentration. Howe (4) has developed a fundamental mathematical expression to characterize the mechanism of flotation. The model, which considers hydraulic conditions and predicts effluent quality, is

$$\frac{C_o}{C_i} = \exp\left(-\frac{V_r}{\frac{Q}{A_h}}\right) \quad \ldots\ldots\ldots\

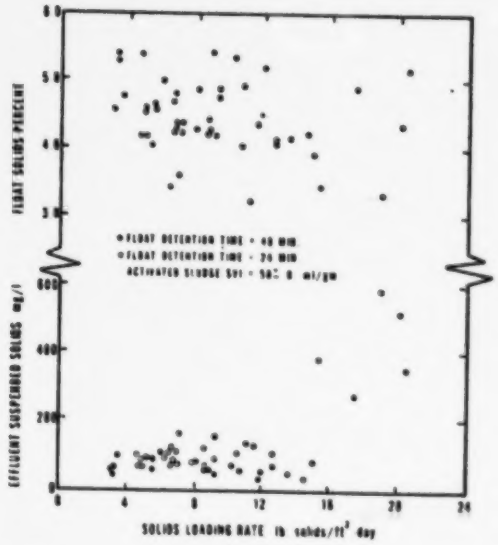

FIG. 2.—FLOTATION PERFORMANCE VERSUS SOLIDS LOADING RATE

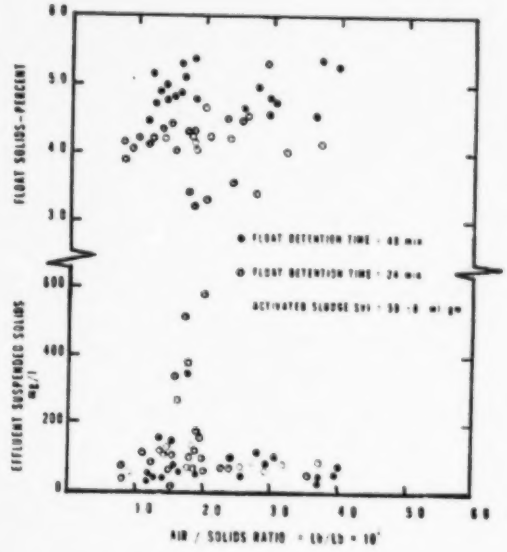

FIG. 3.—FLOTATION PERFORMANCE VERSUS AIR/SOLIDS RATIO

a function of solids characteristics and operational practices. Consequently, effluent suspended solids, and not removal efficiencies, will be used to establish trend relationships for flotation performance.

Fig. 2 shows the performance of the flotation unit as a function of the solids loading rate. Float detention times of 48 min and 24 min correspond to surface skimming speeds of 1.25 fpm and 2.5 fpm, respectively. Effluent suspended solids concentrations show no trend up to a loading rate of 15 lb per sq ft per day; in that range and above, failure occurred. Float solids were more influenced by float detention time than by the solids loading rate. Fig. 3, a plot of flotation performance against the air/solids ratio, indicates that effluent suspended solids are completely unpredictable by this parameter and, as with the solids loading rate, float solids are largely influenced by the float detention time.

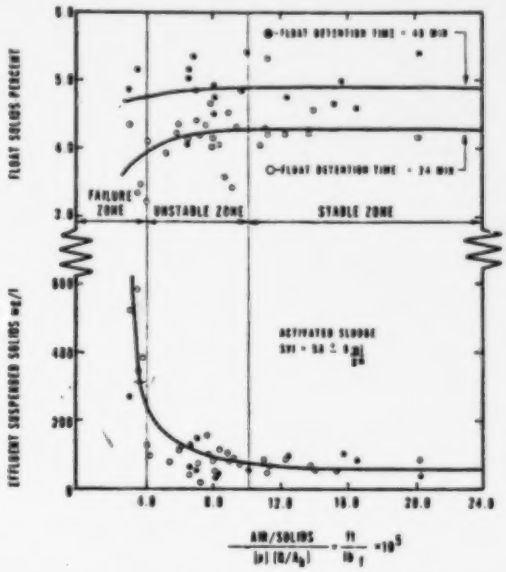

FIG. 4.—FLOTATION PERFORMANCE VERSUS (AIR/SOLIDS)/[(μ) (Q/A_h)]

Fig. 4 shows the influence of the proposed parameter, (Air/solids)/($\mu Q/A_h$) upon flotation performance. Effluent suspended solids concentrations pass through three very definite zones: failure, unstable, and stable. The stable zone represents the area of maximum performance for the flotation unit. In the delineated unstable zone, effluent suspended solids levels show a greater variability. In the failure zone, system breakdown is represented by high effluent suspended solids. Plots of float solids against this parameter indicate a less pronounced trend, with greater sensitivity in the failure zone occurring when a shorter float detention time is utilized. Numerical values of effluent

suspended solids and float solids are applicable only to the Prince William County facility, however, specific values of (Air/solids)/($\mu Q/A_A$) should be approximately applicable to all flotation systems. For example, if effluent quality is the major design goal, calculations should be performed for peak, cold temperature flows at 10 ft per lb × 10^5 ft per lb. On the other hand, if thickening is the major goal of the process, a satisfactory design point would be 5 × 10^5 ft per lb or 6 × 10^5 ft per lb_P at average flows.

Table 2 summarizes the predicted performance of the flotation unit as a function of the solids loading rate, air/solids ratio, and (Air/solids)/($\mu Q/A_A$) for assumed minimum, average and peak flows. The data in Table 2 show that the solids loading rate remains at a conservative level. The Air/solids ratio indicates that the process will be more efficient at colder temperatures. Only the (Air/solids)/($\mu Q/A_A$) parameter indicates that, in a 24-hr period, flotation performance will vary from stable performance to failure in terms of effluent

TABLE 2.—PREDICTED PERFORMANCE OF FLOTATION UNIT AT DESIGN CONDITIONS[a]

Raw wastewater flow, in million gallons per day	Solids load, in pound-solids per square foot per day	Air/Solids, in pounds per pound × 10^2, at pressure = 40 psig		(Air/Solids)/($\mu Q/A_A$), in feet per pound × 10^5, at P = 40 psig		Performance
		Temperature		Temperature		
(1)	(2)	10° C (3)	20° C (4)	10° C (5)	20° C (6)	(7)
0.5 mgd (minimum flow)	4.2	3.1	2.5	18.7	19.6	Stable
1.0 mgd (average flow)	8.0	1.6	1.3	6.7	7.0	Unstable
1.5 mgd (peak flow)	11.6	1.1	0.9	3.4	3.7	Failure

[a] Assume MLSS = 2,500 mg per l.

suspended solids. This result was confirmed with increasing flows during the current study; during minimum flow periods a high quality effluent is produced which progressively deteriorates to complete failure with increasing flow rates. Float solids remain essentially constant at all flows, although skimming at 2.5 fpm produces a tendency for the float to become less concentrated at high flows.

It should be noted that the mass of air utilized in the air/solids ratio is the theoretical amount predicted from Henry's Law (1). Actual amounts of dissolved air are certainly less than 100 % of theoretical and will depend upon fluid characteristics, design of the pressurization system, and day-to-day operational practices.

Float Detention Time.—Fig. 5 shows the characteristics of the float and underflow as a function of the float detention time. Volatile fractions of the sludge streams show very little difference indicating that inert solids are not

preferentially found in the unit's underflow. Operating experience indicates that the underflow sludge volume (5 % to 20 % of the total sludge volume) will increase with increasing float detention time. This phenomenon can be partially attributed to the oxygen uptake of the sludge mass which over a period of time would cause the flotated sludge to lose some of its buoyancy. Operation of the unit becomes one of compromise; i.e., the sludge must be retained long enough to concentrate but not so long as to cause loss of floatability. A float detention time of 24 min was found to be most optimum for this facility. A note of interest is that the underflow concentration is consistently higher than that predicted by the activated sludge SVI. This effect is attributed to the unit's long hydraulic detention time, the mixing of the pressurized final effluent with the mixed liquor suspended solids (which acts as a crude elutriation

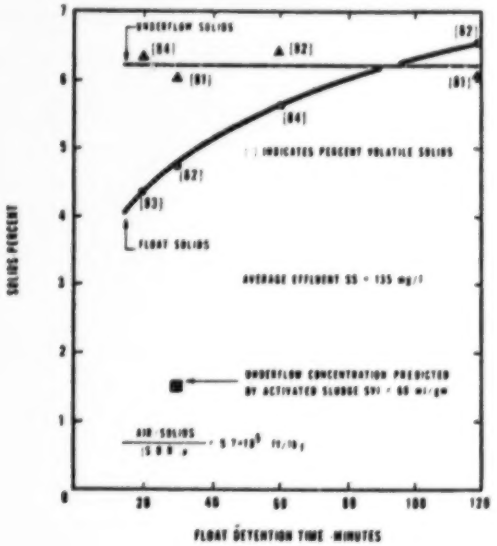

FIG. 5.—SOLIDS CONCENTRATION VERSUS FLOAT DETENTION TIME

process), slow movement of the bottom sludge collectors, and the settlement of compacted sludge clumps, rather than discrete particles, from the deteriorating float.

Process Design.—As shown in Fig. 1, the most troublesome point of operation occurs at the effluent end of the flotation tank. This is the thickest point of the sludge blanket and the sludge which has been in the tank the longest. Deteriorating sludge which settles along the effluent baffle may literally be scoured out of the unit when it meets the higher horizontal velocities caused by the vertical area reduction due to the baffle and bottom sludge collection equipment. Removal of the baffle may not remedy the situation and sludge removal from the influent end of the tank would be complicated from the agitation caused by the air charged influent stream. The best point of float draw-

off may be two-thirds of the distance from the influent end of the tank with float skimmed from both ends of the tank to a central collection point. The use of variable speed drives and timing devices on the sludge collectors would allow optimum operation to be established in the field. Consideration should also be given to lowering the weir loading rate which was designed at 39,000 gpd per ft for this installation.

COST–QUALITY COMPARISON

Table 3 provides a comparison of dissolved air flotation versus gravity clarification with an additional unit process of waste-activated sludge thickening by flotation. Table 3 is subdivided into three distinct areas: physical design, performance quality, and capital and power expenditures. A gravity

TABLE 3.—COST–QUALITY COMPARISON: FLOTATION VERSUS SEDIMENTATION FOR MIXED LIQUOR SOLIDS SEPARATION (1,000,000 GAL. PER DAY BASIS)

Item (1)	Flotation (2)	Sedimentation (3)	Flotation thickening of waste sludge (4)
Physical			
Volume, in gallons	220,000	98,000	22,000
Detention time, in hours	3.4	2.3	—
Surface area, in square feet	2,770	1,670	280
Quality			
Sludge solids, as a percentage	4 to 5	1.5 ~ 2.0	4 to 6
Effluent suspended solids, in milligrams per liter	30 to > 500	10 to 50	30 to > 500
Costs[a]			
Capital	0.044	0.012	0.010
Power	0.025	0.008	0.006
Total	0.069	0.020	0.016

[a] Based on $ per 1,000 gal of main flow stream. Capital costs amortized for 25 yr at 4-1/2 % interest.

clarifier is far easier to operate than a dissolved air flotation unit. Design criteria utilized for the gravity sedimentation unit and dissolved air flotation thickener were the same as those utilized in the existing plant design. Capital costs were obtained from the 1967 plant construction bid. The capital cost of the flotation thickener was assumed to be $15 per ton of dry solids fed to the unit. The capital cost of the sedimentation unit was derived from the actual cost of the plant's final clarifier, adjusted to eliminate the flow volume associated with final effluent recycle for pressurization. Where possible, power costs are based on actual operating expenditures.

Examination of Table 3 indicates that a substantial savings in tankage volume and area requirements would have resulted from use of a conventional gravity clarifier, with or without waste sludge thickening. A better, more de-

pendable effluent could have been produced from the sedimentation tank with a sacrifice in sludge solids concentration and an increase in return sludge pumping capability. A dense waste sludge could have been produced through use of a thickener. If gravity sedimentation had been used, the total costs given in the table indicate that the expenditures associated with mixed liquor solids separation would have been approximately 30 % of the flotation costs. As compared to the use of a flotation unit alone, the combination of gravity sedimentation and waste sludge thickening by flotation would have improved overall operation and resulted in a savings in total cost of almost 48 % ($0.03 per 1,000 gal).

CONCLUSIONS

Conventional design criteria, such as the solids loading rate and air/solids ratio, do not describe flotation performance in terms of effluent suspended solids in the specific application of mixed liquor solids separation. A relationship, $(Air/solids)/(\mu Q/A_s)$, was developed from a fundamental expression derived by Howe (4) and is offered as a more rational design and operational parameter, especially when effluent quality is a major design consideration.

An examination of the economic and quality considerations in Table 3 indicates that dissolved air flotation should have little application for mixed liquor solids separation, particularly when the floc is sheared. For the Prince William County installation, substantial economic savings could have been derived by using gravity sedimentation in combination with waste sludge thickening with an overall improvement in process performance.

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

A_h = horizontal cross-sectional area;
C_i = influent suspended solids;
C_o = effluent suspended solids;
Q = hydraulic flow (feed solids stream + pressurization stream);
V_r = rising velocity of sludge–air bubble particle; and
μ = dynamic fluid viscosity.